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TRANSLATION OF MEASURED VEHICULAR WEIGHTS INTO DESIGN LOADS TO BE USED FOR BRIDGE ENGINEERING

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ABSTRACT

Measurements performed in 1978, 1994, 1996, and 1999 at three locations in The Netherlands were used to derive a statistical model for the axle loads and vehicular loads. The paper discusses the procedure that was used to fit statistical distributions to the measured data and to derive design loads for both axle and vehicle loads. Moreover, a trend analysis of the design loads is presented. Finally, the influence of special permit vehicles on the design load was evaluated.

INTRODUCTION

During the last ten years, TNO Building and Construction Research has carried out an investigation into the modelling aspects of traffic loads on bridges, see for instance Vrouwenvelder & Waarts (1993) and Vrouwenvelder et al (1999). The Dutch ministry of Transport, Public Works and Water Management commissioned the investigations. The aim of the investigations was to find a design procedure, which guarantees a structure with a prescribed level of safety with respect to the various limit states for the intended lifetime, and to replace the old code VOSB (1963).

According to present day standards, the required level of safety is expressed as an acceptable probability of failure or a target reliability index β in combination with a reference period of time for which the probability should be applied. For the Ultimate Limit State (ULS) the anticipated life time of the structure has been set equal to 100 years. For this period a reliability index $\beta = 3.6$ has been chosen according to the current Dutch building regulations (NEN6700). This value corresponds to a probability of 10^{-4}. For sake of comparison: the informative annex of the Eurocode requires a reliability index $\beta = 3.8$. For the service-ability limit states with respect to static deflections and vibrations an occurrence rate of once per year on the average was thought to be appropriate.

DERIVATION OF DESIGN LOADS

For the design of bridges with respect to strength or serviceability a designer needs axle and vehicular loads for the details and distributed lane loads for the design of principal construction parts like the main girders or the cable stayes. Derivation of these loads involves two important uncertainties:

- Extrapolation of (short time) measurement results to design loads;
- Future trends in traffic loads.

A set of measurements done in 1978 (one location: Rheden) and in 1994, 1996 and 1998 at three locations (Moerdijk, Arnhem and Eindhoven) in The Netherlands were used to derive a statistical model for the axle loads and vehicular loads. The measurements lasted some 2 to 7 days each, registrating about 10,000 to 80,000 heavy vehicles per measurement. This large set of data enabled an extensive statistical analysis. Furthermore it was expected that the trend in vehicular load could be analysed in view of the long period between the Rheden (1978) and later measurements. This paper will only consider the ultimate limit state. Furthermore only part of the study is presented, i.e. concerning the axle and vehicular loads. Given the vehicular load, the distributed lane loads can be derived. The procedure for this is already explained in Vrouwenvelder & Waarts (1993) and will not be further discussed in this paper.

PROBABILISTIC DESIGN PHILOSOPHY

For the fundamental case, where there is one load effect parameter S and one resistance parameter R, the basic design requirement in present-day codes is given by:

$$R_d > S_d \tag{1}$$

The index d indicates "design value". The value of S_d should follow from the requirement that the probability of "$S > S_d$" in the reference period is equal to:

$$P\{S_d > S\} = \Phi(-\alpha_s\,\beta) \tag{2}$$

Where

Φ = standard normal distribution;

α_s = influence coefficient for the load;

β = target reliability index.

In the code one may use any combination of characteristic value and partial safety factor that leads to S_d . To find α_s in equation (2) one should in principle perform a complete reliability analysis. For reason of simplification, according to the appendix of ISO 2394, a standardised value of α_s=0.7 is adopted. This means that for the ultimate limit state the design load has a probability of exceedance of $\Phi(-\alpha_s\,\beta) = \Phi(-0.7*3.6) = \Phi(-2.5) = 0.0062$ in 100 years. If all uncertainties in the load model are of an ergodic (not time-invariant) nature, the value S_d has a return period equal to:

$$T_d = t_{ref} / \Phi(-\alpha_s\,\beta) \tag{3}$$

Non-ergodicity may be caused, for instance, by statistical systematic uncertainties, by uncertainties in the traffic or vehicle models, and so on. So, if the load process is ergodic, this corresponds to a load effect with a return period T_d = 100/0.0062 = 16 000 year. For the serviceability limit state, the β value equals 0.0 and so the value of α_s does not matter. The design value simply equals the maximum load effect to be expected in one year.

AXLE LOAD

Distribution type

A statistical analysis was carried out to fit probability distributions to the measured axle loads. On the basis of these probability distributions design values for the axle loads could be derived. The statistical analysis was carried out in two parts. The first part, which is discussed in this section, concerns the derivation of the distribution type. The second part, i.e. the assessment of the distribution parameters, is addressed in the next section. The largest dataset (Moerdijk '98) was used to derive the distribution type. Because of physical circumstances it is supposed that the distribution type is equal for all measurements (locations and dates). Figure 1 shows the frequency distribution of the measured Moerdijk '98 data; Figure 2 shows the cumulative frequency on logarithmic scale.

Both figures are based on 284,881 measured axle loads over a period of 7 days. The shape of the distributions are characteristic for all data sets: at least one mode at about 40 kN, a main mode around 60 kN and a "shoulder' that starts above about 90 kN. These frequency distributions cannot be described by one single standard distribution type. As we are interested in the extreme values, we aim to describe only the tail of the distribution (above a suitable threshold value y_o) with a standard distribution.

There is no other information available except the measured data. Figure 2 shows relative frequencies of exceedance ranging down to about 10^{-6}. The probability of exceedance of the design load is 10^{-11} (the target probability level of 0.0062 mentioned in the previous paragraph divided by the number of vehicles per reference period of 100 years). So, the cumulative frequency distribution needs to be extrapolated over about five orders of magnitude. As illustrated in Figure 3 the result of the extrapolation may highly depend on the choice of the standard distribution type. The four distributions shown Figure 3 result in a wide scatter of design loads. It is assumed that only analysing these four distributions describes the various extrapolation possibilities sufficiently.

The determination of the distribution type is based on the Bayesian approach. For each of the four distribution types the probability is calculated based on the measured data (posterior probability $P\{i|\underline{y}\}$):

$$P\{i|\underline{y}\}=\frac{P\{\underline{y}|i\}P\{i\}}{\sum_{i=1}^{4}P\{\underline{y}|i\}P\{i\}} \quad i=1,\ldots,4 \tag{4}$$

where

i = the distribution type (see indices in Figure 3);

$\underline{y}$ = measured data;

$P\{i|\underline{y}\}$ = the posterior probability of the data being distributed according to distribution type i;

$P\{\underline{y}|i\}$ = likelihood of data $\underline{y}$ in distribution i;

$P\{i\}$ = the prior probability of distribution i.

Distribution parameters and design loads

The design load is derived from extrapolating the tail of the frequency distribution. The result depends on the threshold load y_0. Two considerations lead to the best choice of the threshold load y_0. The higher y_0 the better the statistical distribution describes the tail of the frequency distribution. On the other hand: a higher y_0 leads to less data and therefore a larger uncertainty in the fitted distribution. The optimal threshold load y_0 balances the two considerations.

The cumulative distribution in Figure 6 shows a small kink above 100 kN. A threshold load lower than 100 kN is therefore supposed to be inappropriate. The design load is presented against the threshold load y_0 in Figure 5 to deduce the most suitable value for y_0. The figure also shows the uncertainty margins belonging to the design load for the various threshold loads. The increase of the uncertainty margins with increasing y_0 is based on the decrease of used data.

To calculate the uncertainty margins, 20 samples of axle loads were randomly drawn from the Weibull distribution shown in Figure 6. Each sample had the same size as the measured data set (284,881 axle loads). Subsequently on each of the samples a Weibull distribution was fitted for various threshold loads. This resulted for each threshold load in 20 fitted Weibull distributions from which 20 design loads were calculated. The uncertainty margin per threshold load was estimated as +/- two times the standard deviation of the associated 20 design loads.

Figure 5 shows that a threshold load of 125 kN is the optimum choice for the Moerdijk '98 axle loads. Higher threshold loads lead to some variation in design values, but this variation can be interpreted as statistical fluctuation as the values remain within the uncertainty bands. Apparently, the distribution found at a threshold load of 125 kN also gives an acceptable fit to the data above higher thresholds. If a lower threshold value had been selected, the drawn horizontal line in Figure 5 would have moved up, together with the uncertainty bands, to match the design value (circle) associated with that threshold. Due to this shift, the uncertainty bands would no longer have covered some of the design values for higher thresholds.

This procedure is repeated for the nine other measurements. Figure 7 shows the design loads. It is remarkable that all '94 to '99 measurements result in a higher design load than the old "Rheden '78" measurement. It is also remarkable that the '94 to '99 measurements show no trend in axle load. The analysed data give no basis to conclude whether there is a trend in axle load (based on '78 data compared to '94-'99 data) or that the difference can be explained by the difference in measurement location.

VEHICULAR LOADS

Distribution type, parameters and design loads

The frequency distribution for the vehicle loads resulting from the Moerdijk '98 dataset is shown in Figure 8. The distribution has a similar shape as the axle load distribution, except for one thing: there seems to be a pronounced heavy tail starting above 650 kN. About 30 vehicles form this tail. In a first analysis, the data points in this heavy tail were considered as outliers produced by measurement errors. The considerations were:

- these data points formed only a very small fraction of the data (30 in 80 000)

- the axle configurations of the vehicles were not recognised by the vehicle classification system

Moreover, a possible explanation for the extremely heavy loads could be that two vehicles at close distance were interpreted as one single vehicle by the measurement system.

On the basis of this assumption, distributions were fitted to the data in a similar way as described in section 0 for the axle loads. For the Moerdijk '98 data this resulted in a Weibull distributions as shown in Figure 9 with a corresponding vehicle design load of 1100 kN. Figure 9 shows an overview of the design loads obtained for other locations and measurement periods. As for the axle loads all recent measurements ('94-'98) result in a higher design load than the older "Rheden '78" measurement. The recent measurements on its own do not show a trend in vehicular load. Whether the difference in design load between the '78 data and '94-99' data can be explained as trend in load or as a result of different measurement locations can not be concluded from this data.

Special permit vehicles

At the time of a second analysis, data had become available on permit applications for heavy vehicles. In The Netherlands, it is compulsory to apply for a permit for vehicles with a weight in excess of 1000 kN. Figure 10 shows the frequency distribution of the weights of vehicles, which were granted a permit over the period 1995-2000. The distribution is scaled to enable a comparison with the measured data. In the light of this information, the assumption that the heavy tail of the measured frequency distribution results from measurement errors needed to be reconsidered. Indeed, this tail connects smoothly to the distribution of the permit data. The axle configurations of the vehicles responsible for this tail were scrutinised one by one and it appeared that although these are not standard vehicles, most of them have realistic axle configurations. Hence, it was concluded that the earlier assumption of measurement errors could possibly be unjustified.

To explore the consequences of the heavy tail being real, a distribution was also fitted to the distribution including this tail. The procedure differed from the procedure for the axle loads in two respects. First, it was considered that the fit and the resulting design load should be based on uncontrolled traffic only, i.e. vehicles without a permit. A frequency distribution for the vehicles without permit was obtained by subtracting the frequency distribution of the permits from the frequency distribution of all measured vehicle loads. The result is shown in Figure 11. On this frequency distribution the fit was carried out. Second, two separate populations of vehicles were distinguished, each with its own probability distribution. The probability distribution of the first population, the 'standard' vehicles, is the fitted distribution as obtained in the first analysis. The probability distribution of the second population, the 'special' vehicles, was calculated with a similar fitting procedure, but applied to the vehicles in the heavy tail only. The probability distributions for both populations of vehicles are shown in Figure 11. This figure also shows that if the heavy tail is real, a vehicle design load of 1600 kN should be considered in stead of the 1100 kN that was derived in the first analysis. To enable better founded conclusions about the tail of the frequency distributions for vehicle loads, additional measurements are planned, in which traffic information including axle and vehicle loads will be recorded during a period of one year on various locations in The Netherlands.

CONCLUSIONS

The distribution type and the threshold value for the tail of the frequency distribution heavily influence the extrapolation from measured data to design load. Both items should be given extensive attention when deriving design loads for bridges. A trend in axle or vehicular load can not be observed from the '78 to '99 measurements. The various locations do not show a consistent view. Loads in the dataset that are extremely high should not be regarded as outliers from the distribution too easily. Data in the Netherlands leads to a first impression that this data are real and should not be excluded from the statistical analysis.

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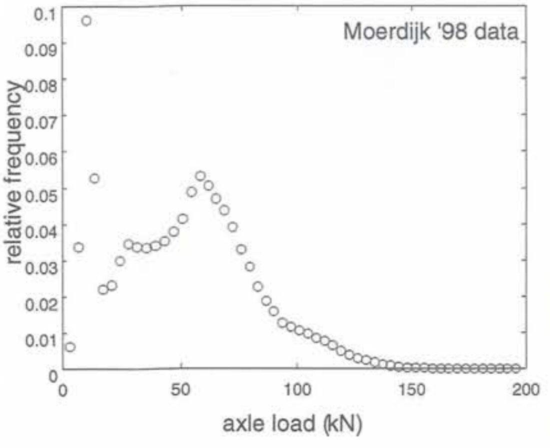

Figure 1 - Frequency distribution of axle loads

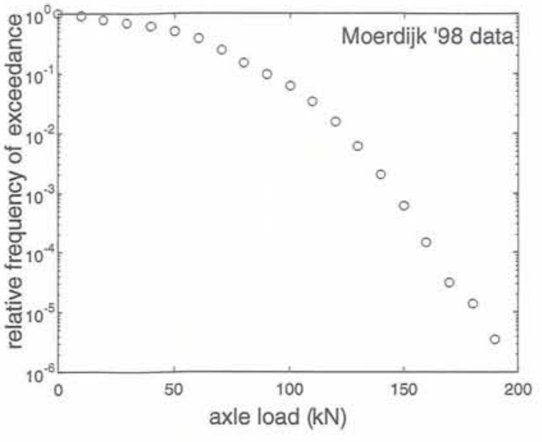

Figure 2 - cumulative frequency of axle loads

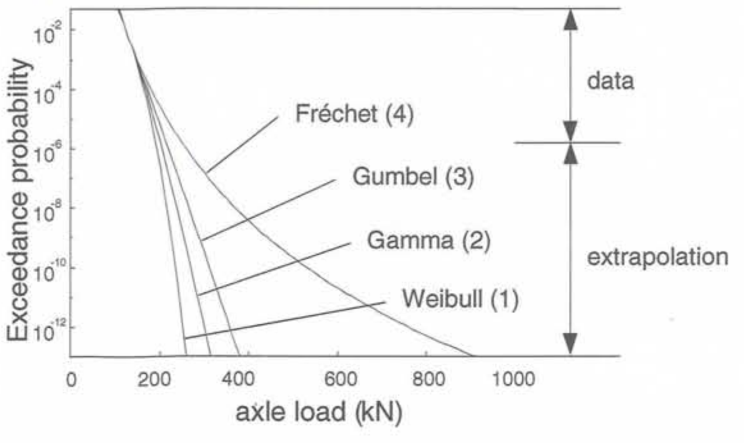

Figure 3 - Typical extrapolations depending on the distribution type

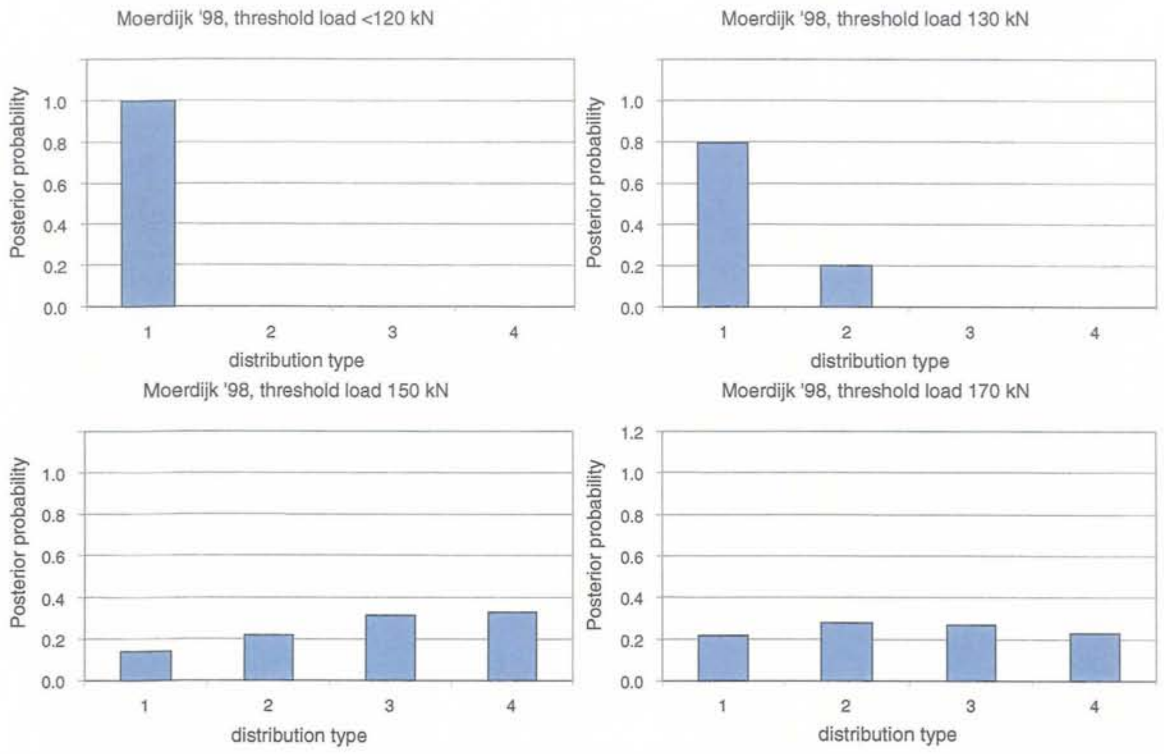

Figure 2 - Posterior distributions of distributions

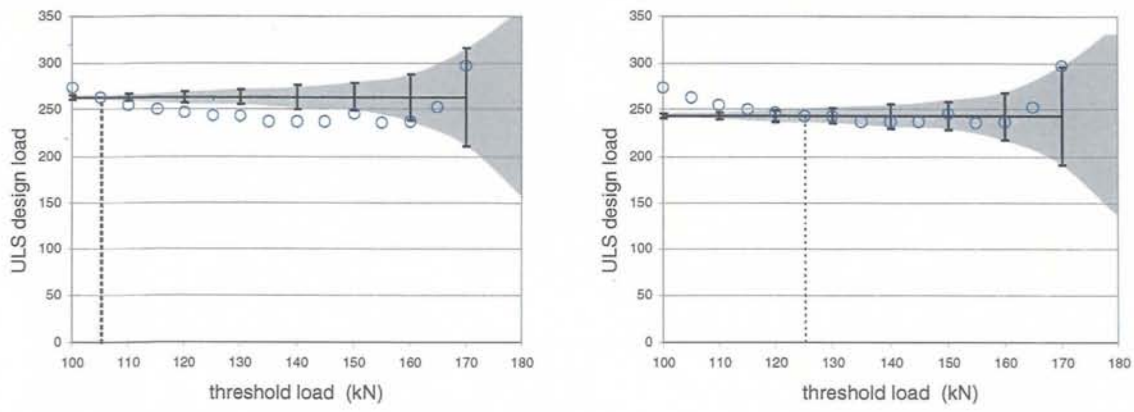

Figure 5 –Left figure: The circles show the calculated design loads as a function of the threshold value y_0. The horizontal line is the hypothetical 'true' design load, calculated from the data at the selected threshold load of 105 kN. The grey area shows which deviations from the 'true value' may occur if the design load would be estimated using a higher threshold value. Apparently, the threshold value at 105 kN yields a biased design load: many of the circles fall outside the grey area, i.e. their deviation from the horizontal line cannot be explained from statistical uncertainty.
Right figure: The The horizontal line is the hypothetical 'true' design load, calculated from the data at the selected threshold load of 125 kN. Now all circles fall inside the grey area, which indicates that the design load, calculated at a threshold of 125 kN is unbiased.

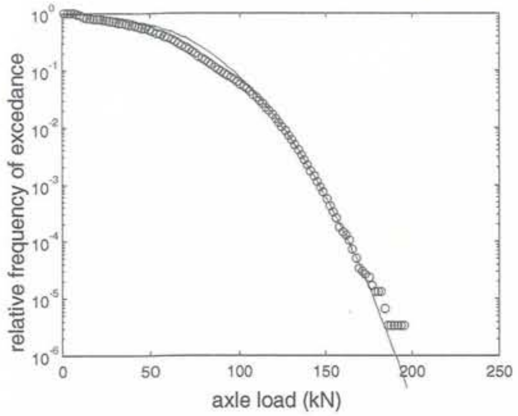

Figure 6 - The circles show the cumulative distribution and the fitted Weibull distribution at a threshold load of 125 kN

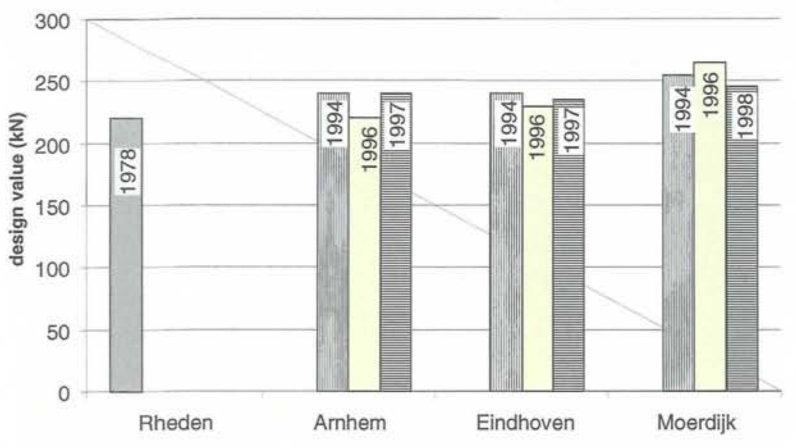

Figure 7 - Design axle loads for the various locations and positions in time

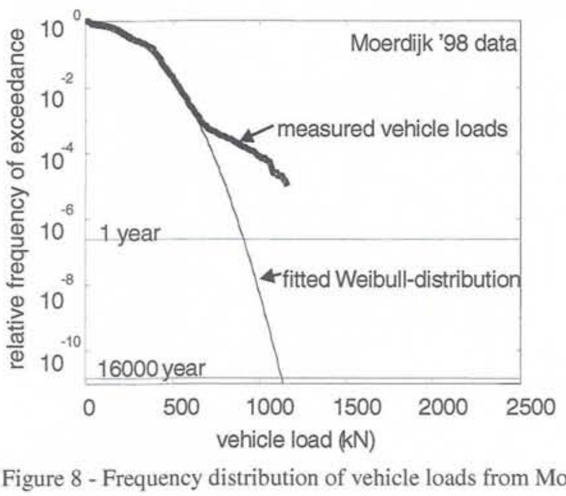

Figure 8 - Frequency distribution of vehicle loads from Moerdijk '98 data and extrapolation in the first analysis

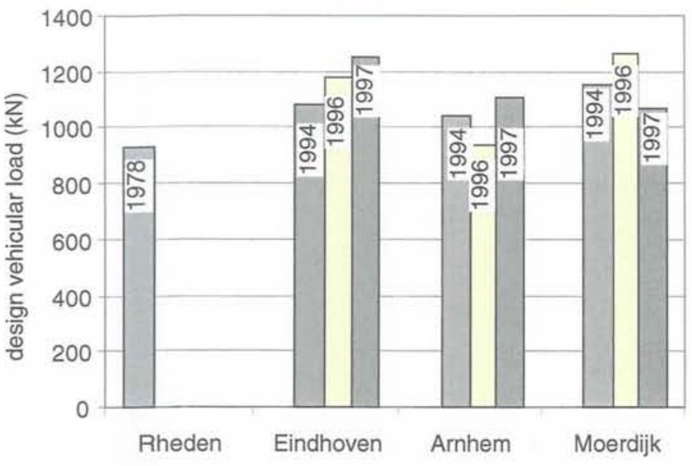

Figure 9 - Design vehicular loads (return period 16000 years) for all measurement locations

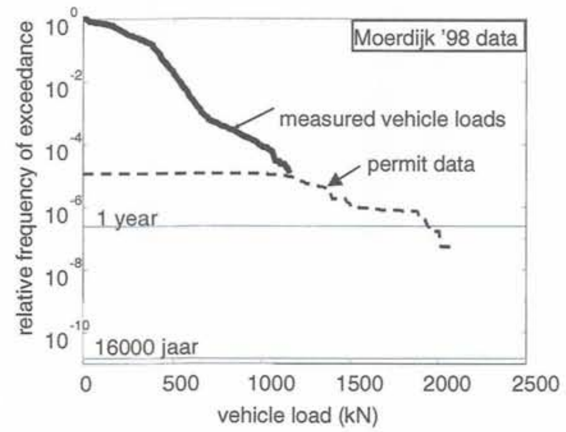

Figure 10 - Comparison of the measured data with permit data.

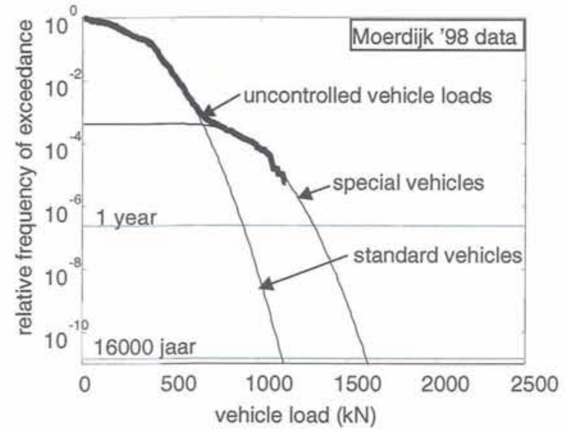

Figure 11 - Fitted distributions on both the population of 'standard' vehicles and the population of 'special' vehicles